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Procedia CIRP 57 (2016) 686 – 691

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49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016)

Understanding sustainability data through unit manufacturing process representations: a case study on stone production

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Abstract

Efficiency of natural stone production processes in quarries directly affects the economic output and environmental performances, such as production lead times and energy consumptions. Knowledge on stone production processes is crucial in making responsible decisions in this business. Having a structured representation of information characterizing the stone production processes will support stakeholders in better assessing production resources in terms of sustainability and productivity. Value stream mapping can provide an overview and guidance for sustainability performance evaluation, but its application is limited. The challenges arise when trying to specifically map and relate sustainability data between processes e.g., variability in lead time and CO_2 emissions. Manufacturing process characterization standards currently being developed by ASTM International manifest the potential to not only fill this gap but also to provide opportunities to characterize and compose manufacturing processes with relevant environmental information and description. This paper shows the application and lessons learned from deploying one such effort towards standardization.

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems

Keywords: Sustainable Production; Natural Stone Production; Unit Manufacturing Process; Composability; Quarrying; Standardization.

1. Introduction

Sustainability, representing a triple-bottom line [1], has become a driver for competitiveness in practically all industrial sectors today. This study focuses on evaluating the sustainability aspects using standard process representations applied on the quarrying processes within natural stone production. The available production technology today demands the use of non-renewable resources, thus causing several negative impacts on the environment. Examples are air pollution from dust and CO_2 emissions from the energy utilized for the quarrying machinery in e.g. the cutting processes [2]. These negative impacts drive the companies operating in this sector to improve sustainability performances of quarrying processes.

Understanding the business processes modelling of an organisation is preliminary for determining its success [3]. Business process was earlier defined as “the combination of a set of activities within an enterprise with a structure describing their logical order and dependence whose objective is to produce a desired result” [3]. This is apt for the natural stone production. The business processes of interest are actual manufacturing processes, which include processes of stone production occurring within quarries.

Understanding the natural stone production process can be rather involved. Several different factors within the production processes vary in quality and performance, and hence the overall output has a large variability as well. Representative factors include:

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems
doi:10.1016/j.procir.2016.11.119

- Natural factors: e.g., adverse atmospheric conditions, natural tension in the rock, colour variations of the stones
- Location of cracks in the stones
- Different manufacturing processes that can be used for the stone forming phases e.g., drilling, blasting, wire sawing, and wedging.
- Weather related uncertainties

With such uncertainties, a structured understanding of processes for natural stone production would further provide a basis for improvement with respect to sustainability performance. From a sustainability point of view, successful stone production within quarries means producing larger volumes with higher output quality, while at the same time, reducing the risk of injury and environmental influences. Sustainability data describing manufacturing processes related to economic (operational) and environmental sustainability will be the focus of this study. This coincides with the goals of the VINNOVA-funded project on "Efficient and sustainable natural stone production" [4], in the context of this research.

We hypothesize that a structured, sustainability-oriented representation of individual manufacturing processes will provide a strong baseline for engineers and managers to meticulously understand and improve sustainability performances of the natural stone production. This paper aims at testing such a hypothesis by implementing a new representation designed for unit manufacturing processes based on an ASTM International [14] standards effort.

The paper is organized as follows: Section 2 reports on the state of art methodologies to map process information within quarrying and mining, Section 3 describes the standard representation used in this study, Section 4 illustrates the application of the standard on a quarry. Section 5 presents a discussion on the practicality and limitations of the standard for the natural stone production industry. Moreover, it shows the standard's future developments.

2. State-of-art on mining and aggregates

Because of the inherent complexity of natural stone production, it follows that a standard aiming at representing quarrying process data under the sustainability lens must be both beneficial to model operational and environmental data. Different methods for process modelling have been used within manufacturing systems [3][5]. In order to specifically investigate the use of process modelling applied to aggregates and mining, the authors performed a literature review within Scopus, Web of Science and Google Scholar databases. From the review, the following conclusions were made:

- the use of simulation models in quarrying exists [6-8], specifically for production-related performances
- various process modelling tools have been applied to model mining and quarrying processes, like for instance Petri nets [9] and value stream mapping (VSM) [10]
- no specific reports addressing the process data in quarrying from a sustainability perspective.

As a result, the authors aim at mapping manufacturing processes of quarries by utilizing standardized representations which supports both operational and environmental data modelling.

3. Standard representations for manufacturing processes

To effectively compute sustainability performance of manufacturing processes and to facilitate decision making, sustainability-related standards are currently being developed by ASTM International [11]. There is a transformation of manufacturing industries from environmental practices based on human experience to environmental practices based on science, specifically on science-based sustainability characterization [12, 13]. That transformation is captured in the Guide for Characterizing Environmental Aspects of Manufacturing Processes [14]. The guide outlines a characterization methodology and proposes a generic representation from which manufacturers can derive specific unit manufacturing process (UMP) representations for meaningful sustainability performance analysis, see Fig. 1.

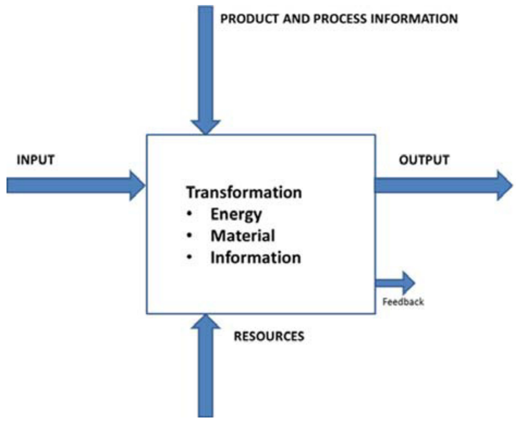

Fig. 1. Graphical representation of a UMP.

Graphical and programming methods can be used to build the UMPs. The creation of a network of UMPs can then be made using the graphical method and transcribed in the formal method (for example in XML).

According to the guide [14], sustainability characterization involves:

1) Identifying the UMPs including key performance indicators and the specifying boundaries,
2) Identifying UMP specific attributes that includes the specific inputs, manufacturing resources, product and process information, and outputs for each UMP,
3) Identifying the transformation functions and listing key UMP specific variables required for calculating the transformation equations.

Inputs include material and consumables; product and process information includes process specifications, production plan, equipment specifications, material specifications, etc.; resources include equipment/tooling, software, etc.; and outputs include product, by-product and waste. Transformation may include material transformation (e.g. mass change, phase change, structure change, deformation, and consolidation), energy transformation (e.g. include chemical, electrical, thermal, mechanical, and electromagnetic) or information transformation such as production metrics (e.g. throughput and overall equipment effectiveness) and environmental metrics (e.g. energy, material, water, emissions, and waste).

The standard purports that in order to realize the utility of the UMPs it is expected that most manufacturers will look towards linking a number of UMP's together to characterize specific production plans for a part, assembly, or a product. This will enable manufacturers to extend the measurement of sustainable performance beyond the process to the product itself. The standard was used as concept guide to model the stone production in three quarries. One of these quarries is used as an example case.

4. Case study

4.1. Overview of Natural Stone Production Processes

In this case study we consider a quarry of grey granite production, where the ideal final products are 2 m^3 stone blocks. In practice, only about 20% of the total production results in the desired final two cubic meters square stone blocks with low variability. The other stone blocks are subsequently classified according to their final shape, their variability. It can be challenging to consider the environmental requirements in this quarry to do any major improvements to production and cost efficiency by acting directly on the process.

The production of one block could consists of four steps. The first step consists of cutting a primary block in the quarry. In the quarry being studied, the use of a wire saw is impossible because of the natural tension in the rock. The process used today to make a primary block is drilling and blasting the drilled holes with explosives (top part of Fig. 2). Once the primary block is made, the second step is to drill and blast the primary block into several smaller secondary blocks.

This second step (middle part of Fig. 2) consists of drilling and wedging specific areas of the block in order to avoid small cracks and discolouring of the stone. This is to create as high quality products as possible.

Secondary blocks are reworked in a third step according to their variability and their shape with a wire saw and drilling/wedging, making the two cubic meter stone blocks from the product, as shown in the lower part of Fig. 2.

The fourth step is to drill and cut the underside of the primary block to make it free.

The location of the final block storage is analysed as one criteria in order to minimize the overall fuel consumption occurring from the inbound logistics, which affects the overall efficiency as well as the environmental impact from the stone production at the quarry.

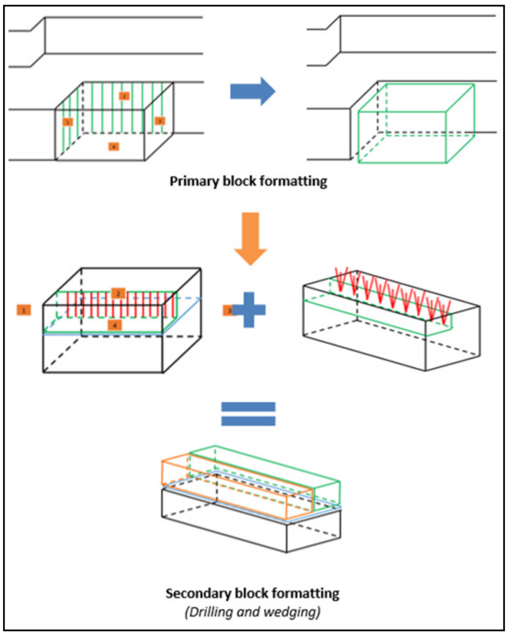

Fig. 2. Illustration of Primary block formatting (drilling and blasting) process

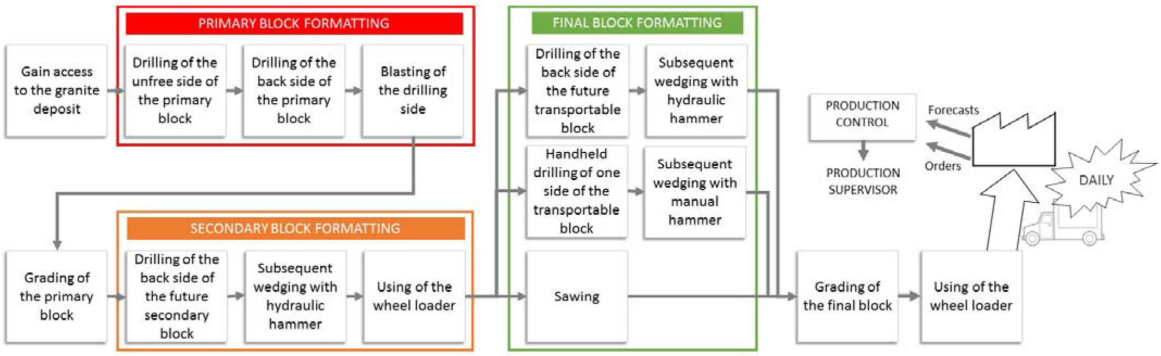

Fig. 3. VSM of the value adding UMPs

4.2. Implementation of the standard

The implementation of the standard on this quarry began by first identifying the different UMPs. In order to identify individual UMPs, it is necessary to understand all the different steps of the production process. To achieve this knowledge, interviews and site visits were conducted to gather the required UMP information from all three quarries. 15 UMPs were identified in the quarries. The flow of the VSM of the 15 UMPs is presented in Fig. 3.

The attributes for each UMP comprising the whole quarrying process is first defined individually. This includes information such as supply and demand of fuel, time, electricity, water, as well as CO_2 emissions. Then by properly creating the connections among individual UMPs, the complete system of the quarry is composed as shown in Fig. 4.

According to the XML syntax, available through the standard guide, it is possible to link attributes of the same type. As inputs and outputs of each UMP; material, energy, wastes and indicators can be considered.

Feedbacks can also be included as outputs of a UMP, for example to calculate the consumption of the resources used by the UMPs. The identified process parameters of each UMP were for example drilling speed, water consumption rate, fuel consumption per meter travelled etc. Those process parameters are then used in the transformation functions inside each UMP to calculate the input/output relationship.

When all UMPs are specified in the formal XML structure, it is possible to compose a network of UMPs by linking outputs and inputs from the different UMPs, as long as they have the same type of data (e.g., "water", "CO_2", "stone"). The creation of the linking variables was in this case done within a prototype software demonstrator created to visualize the composed models of the standard.

This demonstration software can also export an automatically transcribed XML file describing each UMP as well as their relation in compliance with the standard.

4.3. Demonstration software

Finally, the ability to compose UMPs was validated through demonstration software. See Fig. 4 for a screenshot of the network of UMPs, which also can be represented in the XML schema for the ASTM standard.

For this case study, the standard is used for modelling the production of stone blocks with UMPs such as "P3_Blasting" and "P4_Grading" as shown in Fig. 4. The production of stone blocks in the quarries are also linked to, for example, water consumption, fuel consumption and CO_2 emissions. Note that, it is also possible to compose models with the standard that take into account data such as fuel quantity necessary to drive a certain distance to, from, and inside the quarry.

The new guide provides the necessary structure and procedure for identifying and capturing key information needs to assess manufacturing performance. By linking individual UMP models together we can create a network or system of UMP models to represent a production system. The demonstrator built on the standard supports a plug-and-play approach to represent the actual flow of material, energy, and information between manufacturing systems for different levels of automation.

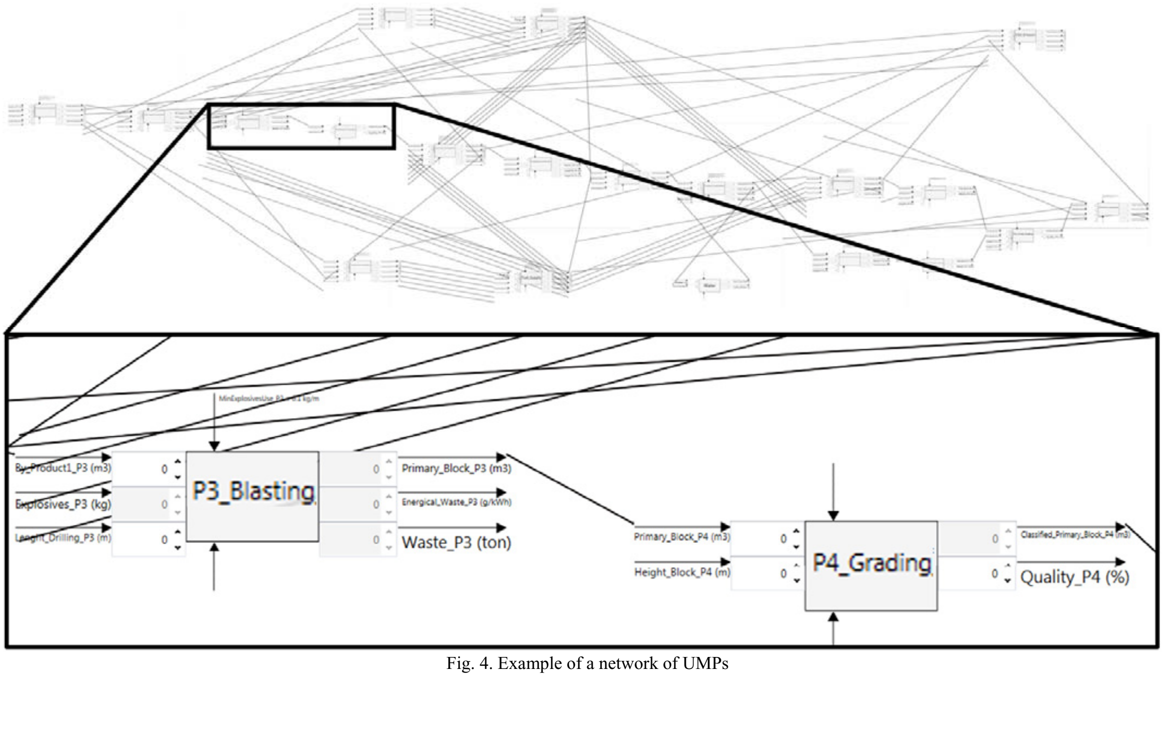

Fig. 4. Example of a network of UMPs

5. Discussion

Standard representations per ASTM E3012-16 [14] provided a baseline for decision makers to holistically understand the natural stone production. UMP representations of individual quarrying processes specifically expanded our understanding of the process performances by tracking the productivity and sustainability related data. Linking multiple UMPs provided the opportunities to build a comprehensive production system enabling analysis and decision support in terms of productivity and environmental.

Collecting the UMP specific information was a crucial part of the study and was done through interviews and site visits. Though initially time consuming, this step was the foundation for the subsequent analysis.

In terms of practicality, the standard was easy to comprehend and use. As was stated in the standard guide, the standard can be used as the backbone while developing modelling tools. In this study, a simple XML based software demonstrator tool was developed. Understanding and implementing the standard using a modelling language such as XML is a learning process.

Besides describing a process, as is possible with tools like VSM, the UMP approach additionally provided opportunities to integrate sustainability and productivity data. It was also easy to account for different types of flows in the same model. VSM is largely used for process mapping, and plots only the time being spent in different processes. It does not factor in the influence of external environmental constraints that is of interest in this study. Hence, the use of VSM is limited whilst studying the quarrying processes under a sustainability perspective.

Some reflections arose from the implementation of the standard through the software demonstrator. During the initial implementation, we noticed that network size of connected UMPs does challenge the implementation of linking variables to read the aggregate data. We are yet to explore the possibility to choose the level of detail (for example, grouping individuals UMPs into one consolidated UMP). There are also opportunities to test different scenarios (i.e., same inputs and outputs but different scenarios for the equations of transformation.)

6. Conclusion and Future Directions

The purpose of this paper is to explore the application of a related ASTM International standard and present lessons learned from its implementation. As described above, the ASTM standard proposes a generic representation from which manufacturers can derive specific UMP representations. These representations are considered as key to achieve meaningful sustainability performance analysis.

To demonstrate the standard's utility, we considered a case study related to natural stone production, since its sub-processes are influenced by high variability, and therefore a structured knowledge representation aids in the business decision making process. Within the case study, we implemented the ASTM standard in order to guide the relative understanding of the sustainability and productivity aspects, both at a unit process level and at a holistic production system level. Preliminary implementation through a simple software demonstrator tool, showed that the standard seems to be easily applicable, adaptable, and helpful for decision support.

Future directions of the work includes (1) improving the prototype tool for the purpose of generalizing its capability to become relevant to any unit manufacturing process, (2) validating its features and general functionality through a formal user evaluation study, and (3) the further development of the prototype tool via a web-based interface, so that other researchers can use its architecture for their own analyses.

A more generalized prototype tool would demonstrate the methodologies robustness to several kinds of analyses, including traditional performance criteria as well as sustainability considerations. From a broader perspective, this work provides insight into the identification of requirements for the implementation of the ASTM standard and its supporting tools. If the standard gains wider adoption, these lessons learned will be critical for moving towards a sharable, distributed manufacturing network, composing of multiple organizations and their suppliers.

Acknowledgements

The authors would like to acknowledge the support from Gauti Asbjörnsson for aiding the cause to conduct the case studies and promoting the work for this paper.

This work was funded by VINNOVA (Swedish Agency for Innovation Systems) through the project "Effektiv och uthållig naturstensproduktion". This work has been carried out within the Sustainable Production Initiative and the Production Area of Advance at Chalmers. The support is gratefully acknowledged.

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